Growth optimization of $Ga_xIn_{1-x}As_yP_{1-y}$/GaAs(0.98 μm) quantum wire heterostructures

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The strain-induced lateral-layer ordering technique has proven itself to be a viable method for creating quantum wires (QWRs) via molecular beam epitaxy. In an effort to achieve emission at the technologically important 0.98 μm wavelength, $Ga_xIn_{1-x}As_yP_{1-y}$ QWRs formed on on-axis GaAs substrates using $(GaP)_m/(InAs)_n$ short-period superlattices (SPS) are investigated. The growth parameters, such as the growth temperature, the source switching pause scheme, and the group-V source flow sequence are optimized to create QWRs with emission near 0.98 μm. For structures utilizing abrupt switching between constituent layers, it was determined that the optimal temperature at which to grow the $(GaP)_{2.2}/(InAs)_1$ SPS on GaAs was 480 °C. By introducing pause times and additional group-V source coverage to the growth scheme, the quality of the QWR heterostructure is markedly improved. The existence of a lateral composition modulation in the growth plane is evidenced by the low-energy emission (redshift) with respect to the bulk $Ga_xIn_{1-x}As_yP_{1-y}$, and the highly polarized nature of the photoluminescence (PL) spectra. Furthermore, the effects of the barrier material between QWR layers (in the growth direction) on the temperature stability of PL peak wavelengths near 0.98 μm were studied. The temperature induced wavelength shift depends on the barrier material, barrier thickness, and the composition of the SPS used in the QWR region. A minimum PL peak wavelength shift of about 200 Å between 77 and 300 K was observed in the $Ga_xIn_{1-x}As_yP_{1-y}$ QWR system with $Ga_{0.51}In_{0.49}P$ barriers. [S0734-211X(98)14903-X]

I. INTRODUCTION

In the last decade, much emphasis has been placed on creating two-dimensionally confined quantum wire (QWR) heterostructures.[1] These structures involve an additional degree of carrier and optical confinements than the currently exploited technology of one-dimensionally confined quantum wells (QWs). Injection laser devices utilizing the quantum size effects (QSEs) of QWRs are theoretically predicted to have improved performance in terms of reduced threshold currents, narrower spectral linewidths, and reduced temperature sensitivity.[2,3] Such laser devices improving on current technology will be in great demand in the future as data and communications networks move toward photonic-based systems.

The strain-induced lateral-layer ordering (SILO) process has been shown to create lateral composition modulation *in situ* during molecular beam epitaxy (MBE) growth.[4] That is, carrier confinement is achieved in a direction parallel to the plane of the (001) growth surface instead of perpendicular as occurs in standard QWs. This modulation occurs during the growth of a short-period superlattice (SPS), generally consisting of alternating pairs of binary compound semiconductors whose relaxed lattice constants lie on either side the lattice constant for the host crystal (e.g., $(GaP)_m/(InP)_n$ on GaAs). Thus, the SPS creates alternating layers of compressive and tensile strain. A key point in this process is that the thicknesses are engineered so that these alternating layers compensate each other, and the overall strain of the SPS is near zero with respect to the host lattice. However, strain forces exist between the constituent layers of the SPS. According to a thermodynamic model developed by Glas[5] for III–V alloys, these finite intrastructural strain fields can result in laterally modulated growth being more favorable than random alloy formation, and therefore lateral ordering can occur during growth.

Combining the lateral composition modulation created using the SILO process with standard QW growth techniques, two-dimensionally confined QWRs can be realized. Because this process is *in situ*, damage and postgrowth processing related defects are avoided. Additionally, because lithographic techniques are not necessary for the SILO process, high quantum wire densities can be achieved ($\sim$50 per μm). Quantum wires have been achieved in the GaInP on GaAs,[6] GaInAs on InP,[7] and GaInP on $GaAs_{0.66}P_{0.34}$[8] material systems through the application of the SILO technique.

The research reported here involves the application of the SILO process to the $(GaP)_m/(InAs)_n$ SPS on GaAs material system. Previous studies have shown that $(GaP)_p/(InP)_q$ on GaAs based QWRs had photonic emission $\sim$0.7 μm at room temperature. It was anticipated that replacing the InP layers with the lower band gap energy InAs would also decrease the emission energy from the resulting QWR structures. The target for the emission was 0.98 μm, a greatly important wave-

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length regime for its application to the pumping of erbium doped fiber amplifiers.[9]

Following the SILO process constraints, the $(GaP)_m/(InAs)_n$ SPS does indeed utilize constituent layers whose lattice constants lie on opposite sides of that for the host lattice. Thus, layer thickness and ratios can be calculated to satisfy the near-zero overall strain condition. In contrast to earlier studies with the SILO technique, however, the $(GaP)_m/(InAs)_n$ SPS uses different group-V sources for each constituent layer. This adds additional complexity because of the concerns involved with the source switching of group-V fluxes.

In this article, we report on the creation of GaInAsP QWRs on GaAs utilizing the $(GaP)_m/(InAs)_n$ SPS. As part of this study, experiments were conducted to optimize the growth conditions, including the growth temperature and source switching scheme. In addition, data are presented comparing the effects of barrier material (i.e., GaAs and GaInP) on these QWRs.

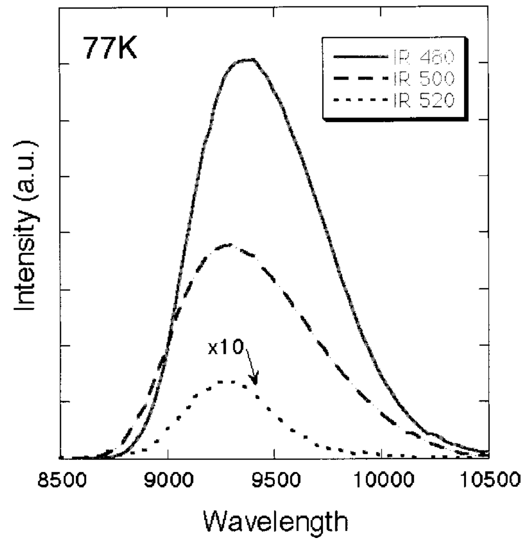

FIG. 1. Photoluminescence spectra measured at 77 K for the $(GaP)_{2.2}$/$(InAs)_1$ SPS samples grown at three different temperatures using GaAs vertical barriers.

II. EXPERIMENT

For this research, samples were grown in a gas source MBE (GSMBE) system, details of which have been previously reported.[10] High purity elemental group-III source fluxes (Ga and In) were provided by standard effusion cells, and group-V material (As and P) were generated using injection of thermally cracked hydride gases (AsH_3 and PH_3). The group-V flux was managed by mass flow controllers, with typical flow rates of 1–5 sccm. A reflection high-energy electron diffraction (RHEED) unit was employed to monitor the growth surface as well as to calibrate the source material fluxes. Growth rates, $\sim$1 ML/s, were determined from RHEED intensity oscillation data of GaAs and InAs. Coordination of the growth sequence was accomplished using custom designed software and a desktop computer. Standard (001) oriented on-axis GaAs substrates were used.

The exact composition of the SPS studied was $(GaP)_{2.2}/(InAs)_1$. Assuming this pairing yielded a uniform quaternary compound, its lattice constant would be 5.65 Å. Thus, the strain compensation occurs with the selection of this particular SPS, as prescribed in the SILO process. The basic test structures grown consisted of five QWR regions and 75 Å barriers between each of the QWR layers, all sandwiched between 3000 Å $Ga_{0.51}In_{0.49}P$ cladding. Each of the QWR layers was made of 12 pairs of the SPS and the barrier material was either GaAs or $Ga_{0.5}In_{0.5}P$.

The optical properties of the QWR samples were measured using photoluminescence (PL) and polarized photoluminescence (PPL). Excitation for the luminescence spectra was performed using the 5145 Å line of an argon ion laser. The emission signal was measured using a 0.5 m focal length grating spectrometer and a liquid nitrogen cooled Ge detector, using the lock-in technique.

III. RESULTS AND DISCUSSION

The study of these $(GaP)_{2.2}/(InAs)_1$ SPS QWRs was conducted in three initial stages: growth temperature, source switching scheme, and modified source switching scheme. The first set of experiments sought to determine an optimized growth temperature. For these growths the gas switching was abrupt between the GaP and InAs layers. That is, no pause time occurred between the deposition of these alternating layers. Three samples were grown at 480, 500, and 520 °C, as measured by an infrared pyrometer.

Figure 1 displays the 77 K PL spectra from this series of samples. The luminescence peaks occurred at 9420, 9340, and 9300 Å for the samples grown at 480, 500, and 520 °C, respectively. A trend of higher emission energy with higher growth temperature is observed. Possible explanations of this are the evaporation of In from the growth surface as a result of the higher substrate temperature, and the enhanced intermixing of Ga and In in QWRs. A slight In deficiency in the SPS region, caused by the In evaporation, results in a more Ga-rich region than intended, thus leading to a slightly higher energy band gap material. Most notable of the spectra is the fact that the 480 °C grown sample produced the greatest intensity of emitted light. Conversely, the 520 °C grown sample had a very weak PL signal, about 50 times less intense than that of the 480 °C sample. It must also be stated that no PL spectra were observed for measurement at room temperature. This may be indicative of a poor overall crystal quality within the SPS region, likely due to the heavy As–P intermixing in-between layers. The most significant conclusion to make from this series of samples is the condition that the growth temperature be $\sim$480 °C.

Evidence of composition modulation, and thus the presence of QWRs, is suggested by analyzing the emission energy from these samples. If the material comprising the $(GaP)_{2.2}/(InAs)_1$ SPS were to form a uniform bulk semiconductor, it would be a quaternary with a composition $Ga_{0.688}In_{0.312}As_{0.312}P_{0.618}$. The band gap energy of the quaternary can be estimated to be $\sim$1.8 eV at room temperature.[11] However, the emission energy from the

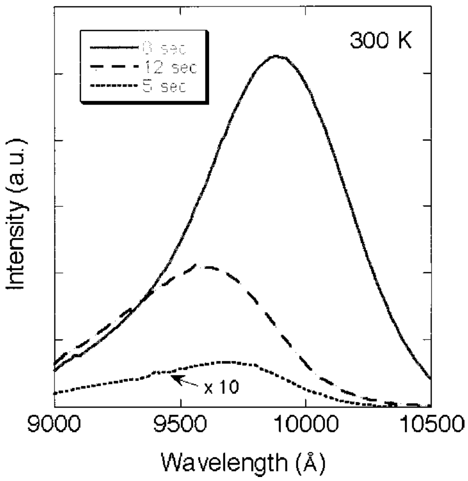

FIG. 2. Room temperature PL spectra from the $(GaP)_{2.2}/(InAs)_1$ SPS samples utilizing growth pauses of 5, 8, and 12 s.

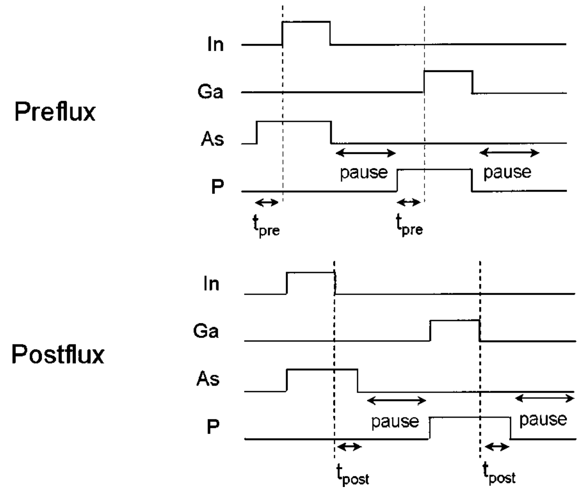

FIG. 3. Source switching diagram for the preflux and postflux schemes used to grow the $(GaP)_{2.2}/(InAs)_1$ SPS.

grown samples is $\sim$1.3 eV. This lower energy value is indicative of the composition modulation which occurs and is consistent with observations seen in other QWRs produced using the SILO process.

For the second series of experiments, a growth pause was introduced in an effort to enhance the QWR formation. In GSMBE, there exists a time transient as a group-V source P or As is turned off. Even several seconds after the group-V source is switched off, a significant amount of residual material remains in the growth chamber which can potentially strike the growth surface. Typically, a time period is allotted during GSMBE where growth is paused and the residual gases are pumped out of the system before commencement of the succeeding layer. Because the individual layers of GaP and InAs were intended to intermix in the growth of the SPS anyhow, it was originally thought that perhaps no growth pause time would be needed. As indicated by the lack of room temperature luminescence from the first set of samples, use of a growth pause may be required after all.

The growth pause utilized in this second series of samples was a period of time after the deposition of each constituent SPS layer where no source flux is intentionally applied. It is during this pause that the residual group-V species are evacuated from the growth chamber by the vacuum pumps. The same SPS structure was grown for the three samples of this second set using 480 °C and pause times of 5, 8, and 12 s. From Fig. 2, it is seen that the addition of 5 s of growth pause time between layers has improved the quality enough so that room temperature PL emission is visible, peaked at $\sim$9680 Å. However, the greatest intensity of the three was seen for the 8 s pause sample, with a peak $\sim$9920 Å. With the longer 12 s pause time, the intensity was reduced and the peak shifted to $\sim$9600 Å.

The relative blueshift of the 5 s pause sample with respect to the 8 s can be explained by the probable incorporation of residual P into the subsequent InAs layer. Phosphorus is a lighter atom and is more difficult to evacuate than arsenic, and 5 s was not sufficient to remove the residual P. Incorporation of this phosphorous would result in a slightly P-rich region. Thus, the emission energy would be slightly higher, and the crystalline quality could be reduced in the SPS. Both of these results are seen to exist in that the 5 s pause sample has a higher peak emission energy but reduced intensity.

A slight blueshift is observed in the 12 s pause with respect to the 8 s sample. It must be remembered that during this pause time, no intentional source overpressure is being applied to the sample. The growth surface remains exposed for this period of time. As the residual gas is being evacuated, little group-V source remains to help protect the surface. As seen in the previous set of samples, In has a tendency to evaporate from the surface if it is not provided with a group-V overpressure. This 12 s pause may be too long in that the surface becomes overexposed, allowing In to leave the growth front. An In-deficient layer would be expected to show a slightly higher emission energy, which is indeed observed in this sample.

In an effort to further improve the SPS growth, the source switching scheme was modified. Figure 3 shows the introduction of a preflux and postflux to the standard growth pause. The preflux is a time period inserted after a pause but before the deposition of the next layer. During this time, the group-V source of the same type as the succeeding layer is exposed to the surface. That is, P is opened to the growth front for a time period prior to the deposition of GaP, and As is opened for a time period prior to the deposition of InAs. Conversely, the postflux method requires that the group-V source remain opened to the substrate for a time after a layer is deposited. For example, the GaP layer is grown, the P remains open for a time after the Ga shutter is closed, and then the normal pause time occurs where no source flux is intentionally applied.

The use of preflux was to ensure ample group-V source material at the surface during the layer deposition. Each constituent SPS layer requires less than 3 s growth time. With both group-III and group-V sources opening simultaneously, there is a finite amount of time before a steady state is

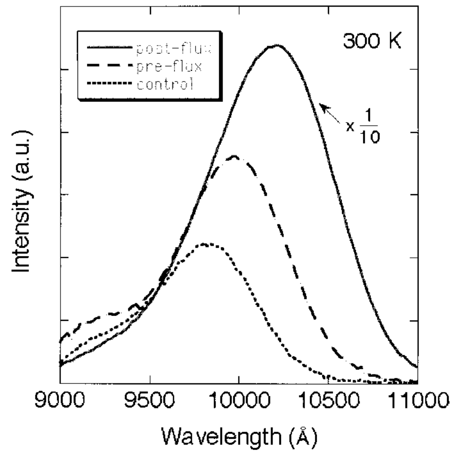

FIG. 4. Growth of the $(GaP)_{2.2}/(InAs)_1$ SPS utilizing a preflux, postflux, and pause-only source switching scheme.

reached. By applying the group-V source prior to the layer growth, this transient time can perhaps be reduced. In addition, this preflux time allows for additional pumping out of the residual gases from the preceding layer while providing some degree of protective overpressure on the surface.

A postflux is similarly provided to ensure sufficient group-V source is available to each SPS layer. During this postflux period, the growth surface is stabilized by the protective overpressure. Additionally, any unbounded and mobile group-III atoms can diffuse across the surface to fill any vacancies, thus creating a smoother growth front.

Three samples were grown for this test group. Two consisted of a 2 s preflux or 2 s postflux, both with 8 s of pause time. The third sample served as a control using only 8 s of pause, essentially a repeat of the best sample from the previous series. All were grown at $\sim$500 °C. Figure 4 shows the resulting room temperature PL spectra from these structures. The most striking feature about the spectra is the overwhelming intensity the postflux pause sample has with respect to the other two. Its peak intensity is nearly 25 times that of the pause-only sample, and 15 times that of the preflux sample. Also worth noting is the fact that the postflux sample has the longest wavelength of $\sim$10 200 Å and the pause only had the shortest $\sim$9820 Å, with that of the preflux sample in between at $\sim$9960 Å. PPL spectra also revealed that the postflux sample had the highest degree of polarization anisotropy of the three samples (Fig. 5).

As a preliminary investigation of the effects of barrier composition, QWR samples were grown utilizing six pairs of $(GaP)_{2.2}/(InAs)_1$. The structure is similar to that mentioned previously, except using either GaAs or $Ga_{0.51}In_{0.49}P$ vertical barrier regions. For the GaAs barrier sample, the observed peak moved from 9400 Å at room temperature to 8990 Å at 77 K, about a 60.2 meV shift. From the $Ga_{0.51}In_{0.49}P$ sample, a peak was measured to change from 10 220 to 10 000 Å, a shift of 27 meV. Thus, not only does the barrier composition have an effect on emission energy, but it also shows the beneficial characteristic of reducing the dependence of emission energy on ambient temperature. A similar effect has been observed previously in the GaInAs/InP QWR system.[12]

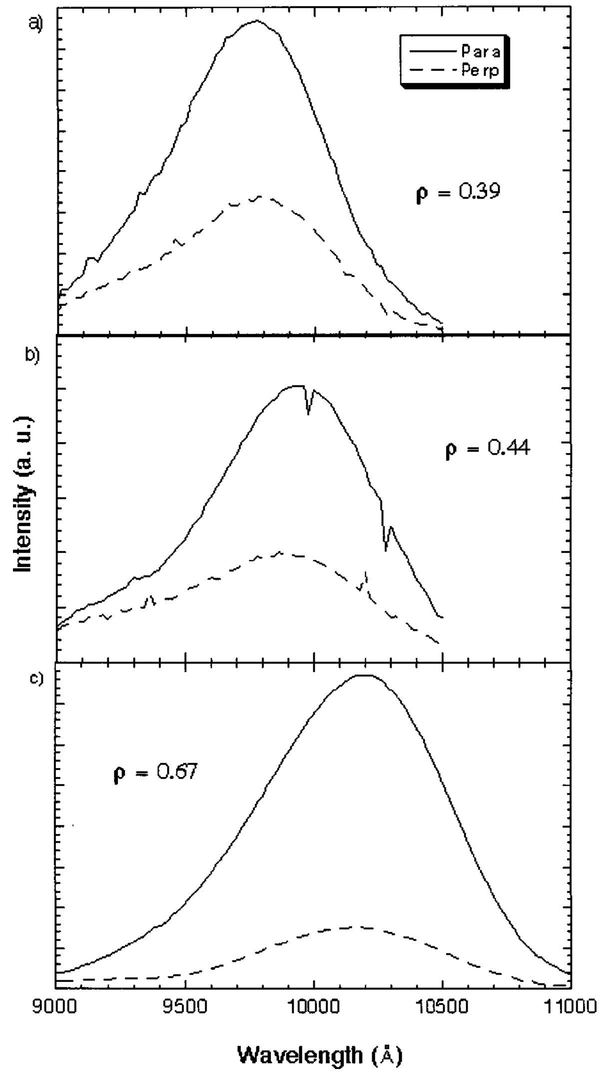

FIG. 5. Polarized PL spectra at room temperature for $(GaP)_{2.2}/(InAs)_1$ SPS grown using (a) 8 s pause only, (b) preflux, and (c) postflux source switching scheme. The polarization value is defined as $\rho=|(I_\parallel-I_\perp)/(I_\parallel+I_\perp)|$, where $I_\parallel$ and $I_\perp$ are the peak luminescence intensities observed with the polarization analyzer either parallel to perpendicular to the QWR axis direction, respectively.

IV. CONCLUSION

The research presented here discussed the application of the SILO process using the mixed group-V pairing of $(GaP)_m/(InAs)_n$ SPS on GaAs, with the goal of creating QWRs with emission in the 0.98 μm regime. Through a series of experiments, growth conditions were determined which realized the objective. Data derived from these QWR samples suggest improvements over QW technology in this same wavelength regime with respect to temperature dependence of emission energy. Thus, the SILO process is once again demonstrated to be a flexible and viable technique to create QWR structures using MBE.

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